

# **OARDC Interdisciplinary Project**

## **Termination Report**

### **Implications of Climate Change for Agricultural Pest Management**

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**Title: Implications of Climate Change for Agricultural Pest Management**

**Abstract:** The thermal requirements of crops and insect pests differ significantly; their differential thermal requirements will govern how climate change impacts pest management needs and practices. To investigate the impact of climate change on pest management and the implications for farming communities, we have connected EPIC, a field-scale crop management model, with a temperature-driven model of insect population development (GILSM). EPIC was used to model the corn and soybean rotation common in the Midwest, and GILSM was programmed to model the growth of nine insect pests of corn and/or soybeans. Output from the model system was input to a geographic information system covering the eight-state corn-belt (Indiana, Illinois, Iowa, Kansas, Kentucky, Missouri, Nebraska and Ohio). The models were driven using GFDL-CM2 climate scenario data developed for the period 1901-2100 as part of NOAA and IPCC investigations of global climate change. Over the past 100 years, crop productivity has increased several fold as a result of improved cultivation methods, fertilizers and pesticides, and plant breeding. In order to remove the confounding of changes in technology and possible climate change over the past century and unknown changes to come in the next century, a standard crop production protocol was used from 1901-2100. Using the crop production practices used most commonly in 2000 (the midpoint of the period), EPIC/GILSM was run for four 50 year periods (1901-1950, 1951-2000, 2001-2050 and 2051-2100) and the changes in crop yield and insect abundance were examined between periods. Nine insect pests found throughout the region were modeled to examine the range of likely responses of insect pests to climate change and the possible change in crop protection needs over the next 100 years. As expected, the model predicted little or no change between the first and second periods. For most species, change was maximum in the third period and less during the fourth period. In every case the isoclines for pest population density and crop productivity moved northwards, but at different rates, resulting in the isoclines for crop damage increasing as they moved northward. In two cases the pest abundance declined locally even as productivity increased, resulting in a net increase in productivity. No allowance was made for changes in agronomic practices or improvements in breeding pest resistance, both of which have helped to improve productivity over the past century.

## Introduction

The thousands of papers published and several new journals established on the subject of global climate change emphasize the importance of this topic that affects everyone on the planet. The “hockey-stick curve” based on tree-ring reconstructions shows a dramatic increase in temperature since the 1980s (Mann et al 1998,1999). Despite early official skepticism (Kerr 2006), this dramatic upsurge in temperature suggests that the planet is not only warming but that the temperature increase is *accelerating*. The Max Planck Institute in Germany estimates a temperature increase of 2.5-4.0°C by 2100 (Schiermeier 2006).

In many regions there is an asymmetry in the warming because minimum temperatures are increasing at about twice the rate of maximum temperatures. Consequently the freeze-free periods in most mid- and high-latitude regions are lengthening, resulting in a 10% reduction in snow and ice extent from 1960 to 2000 (Walther et al 2002). Satellite data show that photosynthetic activity of terrestrial vegetation in a band from 45 to 70°N increased from 1981 to 1991 as a result of an increase in the length of the growing season (Myneni et al 1997).

Climate warming could influence crop production in at least three ways:

Direct effect of changes in temperature, precipitation, and carbon dioxide (CO<sub>2</sub>) levels on plant growth and health.

Indirect effect on plant health via climate-induced changes in herbivore and competitor distribution and abundance.

Indirect effect on plant health via changes in higher trophic level interactions of predation, parasitism, and competition on herbivore and/or competitor distribution and abundance.

Increased temperatures are expected to increase yields in many crops (REFS). However, variability in the amount and temporal distribution of precipitation could also increase yield variability (Nonhebel 1996, Rhia et al 1996). In the tropics this could be disastrous, but in the warm temperate zones these conditions could offset each other for a number of major crops, although a few crops may become marginal and others could become possible. In the cooler latitudes, temperatures are limiting for many crops, so that higher temperature will extend the growing season (Carter & Saarikko 1996) and could increase yields, although Long et al (2006) doubt this. Thus, in Europe and North America the area in which major crops can be grown is likely to increase as the northern limits move northwards and the southern limits move northwards more slowly (Rosenzweig & Parry 1994). Two retrospective examinations of climate change concluded that the effects of global warming have already been detected in increased crop production in Germany (Chmielewski 1992) and Australia (Nicholls 1997).

Many ecological, agricultural, socioeconomic, and human health factors depend strongly on plant and animal phenology. Phenology is therefore increasingly relevant in the framework of global change studies. Many biological processes are affected by climate, and in temperate areas the increasing spring temperature over the past 30 years has caused an advancement of phenological events in plants and animals (Harrington et al 1999, Penuelas & Filella 2001; Root et al. 2003, Jonzen et al 2006). Longer growing season in temperate zones are expected to translate into increased productivity, which should be beneficial. But what is good for the crop is also good for crop pests. While some research has been devoted to climate-induced changes in

insect life-history traits, scant attention has been paid to the impact on pest management and farm profitability. The exception is in forest outbreak insects and diseases (Volney & Cerezke 1992; Virtanen et al 1996; Williams & Liebhold 1995; Volney & Fleming 2000; Woods et al 2005).

There is also evidence of multi-trophic effects in non-pest species: great tits and winter moth (Visser et al 2003), amphibians and fungus (Pounds et al 2006), and dislocation between prey supply and migrant bird demand (Sanz et al 2003). So why is there a near total absence of references to the likely impact of multi-trophic effects on agriculture? Because pest status will not change as a result of climate warming? Unlikely. In their report to the US-EPA on the likely impact of climate warming on agriculture, Stinner et al. (1989) concluded that dislocation was highly probable, especially for multi-voltine, migrant species. This has been reiterated by later authors: most recently Sehgal et al (2006) who warn against the likely problems in the Indian subcontinent. The little that has been published on changing insect life-history traits (Fielding et al 1999; Hodgkinson et al 1999) does not address the implications for pest management.

Pest populations are affected by biotic factors (e.g. enemies and competition), abiotic factors (e.g. climate and soil) and agronomic management practices. Likely impacts of climate change range from expansion in the geographical range of pests, increased risk of invasion, changes in overwintering patterns, natural enemy-pest interactions, changes in population growth rates, change in crop-pest synchrony, pest control factors and spatial and temporal changes in pest complexes. Results obtained through current modeling approaches do not account for all the factors operating (Stinner et al 1989; Sehgal et al 2006). Although modeling studies to project the likely impacts of climate change on agricultural productivity have become very sophisticated in recent years, “agricultural impact assessments still do not account for all important factors” (Schermer 2004). Potential changes in yield losses due to altered dynamics and intensity of pests (insects, plant pathogens, and weeds) under climate change have been completely ignored; an important omission, given the significant role of plant pests in constraining the production of food and fiber worldwide.

In this report we will offer some answers to the questions: How will increasing temperatures change crop-pest synchrony? How will changes in crop-pest synchrony affect pest status? How will pest management needs change with changes in pest status?

## **Hypothesis and Objectives**

This research was based on the proposition that global climate warming will be manifest in *differential* changes in the growth rates of crops and pests. Furthermore, we predicted that these changes will affect pest status at a given location such that some pests will increase in importance, others decrease, and some new pests will emerge. In consequence, we expect that these changes will require new or modified pest management practices, disrupt established practices, and jeopardize agricultural sustainability and environmental health by stimulating increased use of pesticides. To test these predictions and to examine their environmental, economic, and societal implications, we modeled the differential thermal requirements of insect pests and two major crops at a regional scale to predict shifts in the spatial distribution of pest stress induced by climate change.

Our formal hypothesis states that the thermal requirements of pests and crop plants differ sufficiently that global warming will change pest status. Generally, the rate of insect

development and population growth between upper and lower temperature thresholds is proportional to temperature. By contrast, plant growth rate between upper and lower temperature thresholds depends more on the amount of sunlight and availability of moisture. Thus, we predict that a warming trend will favor more rapid insect development over crop growth. During spring months in the Corn Belt, several of the major insect pests could accumulate degree days more rapidly leading to earlier establishment of pest populations while crops are at young, relatively susceptible growth stages. This pattern would result in a lessened ability of crops to outgrow pest damage. The importance of phenological synchrony in affecting the severity of pest damage to crops has been demonstrated for a number of major pest species and their host plants (e.g. European corn borer and black cutworm on corn and Mexican bean beetle on soybean (REFS)), and it is not uncommon for insect development to be tightly bound to their host plant's phenological stage. Thus, insect development can be severely hampered if synchronization with the host plant lags only a couple of weeks out of phase. Therefore changes in pest status could be positive or negative. From our point of view, the negative aspects of synchrony center on either insect development being faster than crop growth, resulting in larger insects earlier, or insects becoming more abundant earlier, when a crop is particularly vulnerable.

To test this hypothesis, our objectives were to:

1. develop a crop-pest interaction model of climate-induced change in pest pressure on corn-soybean agriculture in the Midwest Corn Belt.
2. apply the model to predict the likely changes to pest pressure as carbon dioxide levels, temperature, and precipitation patterns change over the next 100 years.
3. use these predictions to develop strategies for maintaining sustainability of corn-soybeans agriculture that will minimize socioeconomic disruption as warming changes pest status.

## **Objective I – Model Development**

To investigate the shifts in plant and pest abundance, we programmed the plant physiological response to temperature, moisture, and carbon dioxide levels and temperature-dependent pest population dynamics into EPIC, a crop model, modified by the addition of a programmable, time-distributed insect population model, GILSM.

The Erosion-Productivity Impact Calculator (EPIC) model was originally developed to assess the effect of soil erosion on soil productivity and has been expanded to simulate other processes important in agricultural management (Sharpley & Williams, 1990). Recently, most of the EPIC model development has been focused on problems involving water quality and the effect of CO<sub>2</sub> change on crop growth and water use.

The area considered by EPIC is generally a field-size area, up to about 100 ha, where weather, soils, and management systems are assumed to be homogeneous. Farms may be subdivided into fields, soil types, landscape positions, or any other configuration of interest. EPIC operate on a daily time step, although some variables may be simulated at time steps down to 0.1 hr. The model offers options for simulating a number of processes: potential evaporation of water, erosion and sedimentation, and peak runoff. EPIC can be used to compare management systems and their effects on nitrogen, phosphorus, carbon, pesticides, and sediment. The management components that can be simulated include crop rotations, tillage practices, irrigation schedules, drainage, fertilization practices, and pesticide application; livestock grazing and

manure management are also simulated. Thus, it can be used to evaluate different land management strategies by considering sustainability, erosion, water supply and quality, soil quality, plant competition, weather, and pests.

The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control. The weather variables required by EPIC are precipitation, maximum and minimum temperature; solar radiation, wind speed and relative humidity are also used, but can be estimated by the program. EPIC uses a single model structure for simulating all crops with each crop having unique values for the model parameters. It is capable of simulating growth for both annual and perennial crops. The management capabilities that concern us are crop rotation, fertilizer regime, and tillage practice.

Insect population growth models are driven by temperature and food availability. The details differ between pests; primarily reproductive rates, physiological rate constants, and thresholds, but also sex ratios and responses to day length. The particular model we linked to EPIC is the Generalized Insect Life-System Model (GILSM) that generalizes Taylor's (REF) Japanese Beetle Life System Model (JBLSM). JBLSM is similar in structure to Stinner et al's (1974) corn earworm (*Heliothis zea*) model (SICM). SICM was used by Stinner et al (1989) to investigate the probable impact of warming on soybeans due to northward extension of the corn earworm's range. GILSM simulates daily cohorts through their life-cycle. Eggs laid on a given day constitute a cohort that progress through their larval, pupal, and adult stages, changing from stage to stage on a day-degree schedule.

The proportion of eggs laid by a female on any particular day is a function of temperature and adult age. Each day the number of eggs each female lays is calculated from her age and that day's temperature, then all the day's egg production is combined into a single cohort. Mortality inflicted by predators, insecticides, and food shortages may be incorporated into the model explicitly, but in this version were incorporated as stage-specific, temperature-dependent, and independent mortalities. The progress of each cohort, creation, development, mortality, and death were recorded in a linked-list database containing cohort-specific variables (cumulative food consumption, size, age, stage, and diapause or migratory status). When a cohort dies, summary information is saved and its database is deleted, releasing the memory for future generations.

Life-history parameters to program GILSM were obtained from the literature for nine insect pests of corn and/or soybeans. Temperature drives the model by calculating physiological time (day-degrees) from the maximum and minimum temperatures and upper and lower developmental thresholds using Allen's (1976) algorithm.

EPIC and GILSM were run in parallel on a daily basis with crop damage calculated only at harvest. The linkage between EPIC and GILSM are not ideal but were considered adequate for the present purposes. A daily linkage would provide better feedback from plant to insect population and prevent the occasional insect population explosion that would not have occurred if overexploitation of the crop had resulted in insect mortality. Both models output a range of variables over a range of time frames; daily, monthly and annual.

The composite EPIC/GILSM model was run at the resolution of the county for an eight state region of the corn belt: Illinois, Indiana, Iowa, Kansas, Kentucky, Missouri, Nebraska, and Ohio. The area comprises 813 counties, is approximately 1400 x 400 km (~216,000 mi<sup>2</sup>), and covers a large part of the area where corn and soybeans are grown separately and in rotation

(>60% of all corn and soybeans). It is diverse both latitudinally and longitudinally, in soil, elevation, and climate, and could reasonably be expected to clearly show changes in pest population and crop yield isoclines in response to climate change. Data and functional relationships governing vital rates in corn, beans, and their insect pests to parameterize the model are well established and many interactions have already been encapsulated in management models.

Weather data were obtained from NOAA's Geophysical Fluid Dynamics Laboratory (GFDL). The GFDL data are daily simulated temperature and precipitation obtained using the CM2.0 Atmosphere-Ocean General Circulation Model (AOGCM) model. The particular scenario selected was the "CM2-SRES\_B1" scenario developed for the Intergovernmental Panel on Climate Change Fourth Assessment (IPCC-4A) driven by observed (1861-2000) and projected (2001-2100) CO<sub>2</sub> production based on an assumed international responses to climate change. This particular scenario simulates observed climate conditions from 1861 to 2000 very well and projects CO<sub>2</sub> stabilization at 550 ppm by 2100. Other scenarios are more pessimistic, projecting much higher stabilization (>700 ppm CO<sub>2</sub>). Output from CM2.0 are at 2° latitude and 2.5° longitude intervals over land. 72 points cover and completely enclose the corn-belt region of our study. Daily (simulated) records of maximum and minimum temperatures (°C) and precipitation (mm) from 1 January 1901 to 31 December 2100 were downloaded from NOAA's website. Estimates for each of the 813 counties in the region were interpolated from the nine nearest GFDL points. These estimates were used to drive EPIC/GILSM runs for each county for 200 years. On the advice of CM2.0 developers and other users of the CM2.0 scenarios, the models were run in four half-century sets: 1901-1950, 1951-2000, 2001-2050, and 2051-2100, and changes between the half-century sets used to infer changes in pest-crop interactions.

Output from the models was linked through a filter to a geographic information system, ArcInfo (ESRI 2008) for data storage, display and analysis. GIS covers for corn and soybean area planted, crop yield, soil, elevation, and weather were also created. Change in crop production and insect population parameters were inferred from the movement of isoclines from one period to the next.

## **Objective II - Computer Experiments**

Nine insects, pests of corn and/or soybeans were simulated using EPIC/GILSM: two beetles, bean leaf beetle and Mexican bean beetle; six moths, armyworm, black cutworm, corn earworm, European corn borer, stalk borer, and velvetbean caterpillar; and a cicadellid, potato leafhopper. Each of these species is currently a sporadic and occasionally serious pest of one or other crop in at least part of our study area. They were chosen to include resident and migrant species and to represent species feeding on one or both crops. Table 1 summarizes their life-styles.

The corn earworm is multivoltine in the south, with the second generation damaging corn and the third and fourth generations damaging soybeans. The corn earworm is resident throughout our study area, but also migrates north mid-summer and causes serious damage to sweet corn, and occasional damage to field corn. Populations do not have sufficient time to develop on soybeans, and thus it is a marginal soybean pest in the Corn Belt. If corn earworm overwintered further north, population levels in the north could become large enough to cause greater damage to soybeans.

Table 1: Life history characteristics of the insect pests investigated

Pest Species ( <i>Latin Name</i> )	Corn	Beans	Resident	Migrant	Voltinism*
<b>Coleoptera</b>					
Bean Leaf Beetle ( <i>Ceratoma trifurcata</i> )		√	√		1-2
Mexican Bean Beetle ( <i>Epilachna varivestis</i> )		√	√		2-3
<b>Lepidoptera</b>					
Armyworm ( <i>Pseudaletia unipuncta</i> )	√			√	2-3
Black Cutworm ( <i>Agrotis ipsilon</i> )	√			√	1-2
Corn Earworm ( <i>Heliothis zea</i> )	√	√	√	√	1-2
European Corn Borer ( <i>Ostrinia nubilalis</i> )	√	√	√		1-3
Stalk Borer ( <i>Papaipema nebris</i> )	√	√	√		1
Velvetbean Caterpillar ( <i>Anticarsia gemmatilis</i> )		√		√	1-3
<b>Homoptera</b>					
Potato Leafhopper ( <i>Empoasca fabae</i> )		√		√	3-5

\* Voltinism as of 2000

The armyworm and black cutworm overwinter in the south, and the velvetbean caterpillar, a pest of soybeans, overwinters only in south Florida and Central America. The potato leafhopper, once thought to overwinter only on the Gulf coast is now known to overwinter as far north as Tennessee. Warmer winters further north could move the overwintering ranges of these insects northwards and increase the size of spring migrations.

The European corn borer, Mexican bean beetle, and bean leaf beetle are resident species, passing the winter as eggs or in a diapausing stage. They have two or more generations per year over most of our study area. European corn borer is mostly bivoltine, but is univoltine in the coolest, most northerly parts of our region and occasionally has three generations in parts of the region. Higher temperatures and longer growing seasons could increase the area of trivoltinism.

It is known that the developmental time of bean leaf beetle would decrease from 90 to 60 days with a 3°C temperature increase during April and May (REF). A large enough temperature increase could result in soybeans being attacked at a more vulnerable growth stage and more rapid development by the bean beetle could result in a second generation population peaking before soybean senescence leading to increased damage on maturing seed pods. In contrast, fecundity and larval survival of Mexican bean beetles on soybeans are reduced by high temperatures and low humidity, possibly resulting in reduced risk.

The stalk borer is univoltine throughout its range. It seems probable that winter diapause is obligate and adaptation to bivoltinism is unlikely to evolve. However, if warming resulted in a markedly increased day-degree accumulation *and* a non-diapausing mutant were to appear (as is occasionally seen in Gypsy moth (*Lymantria dispar*) (REF)), the life-history strategy and pest



status of this species could change dramatically.

### **Assumptions**

Idealized forcing scenarios, such as those developed for the IPCC-4A, typically concentrate on single forcing variables, holding all others constant. For example, the 1% per year CO<sub>2</sub> increase has gained wide acceptance in the climate modeling community, because they facilitate the analysis of modeled climate responses as well as comparisons between forcing agents (Stouffer et al 2006). While not intended to specifically represent past or future trends in the real world's atmospheric composition, this rate of CO<sub>2</sub> increase produces a forcing change in a straightforward manner that avoids ambiguities associated with more complicated and realistic scenarios. For example, by prescribing a 1% CO<sub>2</sub> increase to be the only forcing agent, differences in the spatial and temporal distributions of other factors such as ozone and aerosols (just two of the factors contained in more realistic forcing scenarios) do not confound results. Of course, by adopting an idealized forcing scenario the ability to directly compare the model results with historical observations is lost. For this reason, most modeling groups conduct both idealized and more realistic forcing experiments. We were advised by climate modelers at NOAA and NASA to start with a uniform experimental frame, using the climate data from the "CM2-SRES\_B1" scenario to force our model, thus making our study an extension of the single factor modeling approach.

By adopting this approach, we sacrificed "realism" for "insight" into likely changes at a synoptic scale. Absolute values of crop production or insect population variables cannot be interpreted either forwards or backwards, but *relative change* between periods is interpretable. Accordingly, the following assumptions are implicit in the experiments:

1. Agronomic practices are spatially homogeneous;
2. Insect vital rates are spatially homogeneous
3. Insect evolutionary changes are adaptations to the forcing variable only;
4. Geographic variation is the only spatially inhomogeneous state variable;
5. Climate is the only forcing variable

Clearly, Assumptions 1 and 2 are restrictive. Assumption 1 is particularly unrealistic, as elevation, soil type, and growing season vary substantially across the Corn Belt region, making for quite large differences in planting and harvesting dates, for example. Fertilization and tillage practices are also highly site specific. Assumption 2 is less restrictive, as many insect vital rates are temperature-dependent and are unlikely to vary substantially over the region except in response to temperature. However, some rates are modified by agricultural practices and thus are linked to Assumption 1. Insects can evolve quite quickly (consider pesticide resistance, but see below), but as climate is the only forcing variable, Assumption 3 is not too restrictive.

### **Data**

The agronomic practices adopted for this study are those commonly used in Illinois in the year 2000. Illinois, because it is the middle state in the region and 2000 because it is the middle year in the scenario. Planting and harvesting dates were set to 6 May and 19 October, respectively for corn and 24 May and 11 October for soybeans. Tillage was minimum till and the only fertilizer was green mulch; i.e. no inorganic fertilizers were added and only crop residue and fixed nitrogen fertilized the crops. No pesticides were applied, so scenarios were worst

possible case for insect damage and crop loss.

The insect vital rates used are given in Appendix I.

### ***Output***

Twenty-five variables were recorded of which nine were chosen for mapping and analysis: crop yield without insect pests, crop loss due to each insect pest, the day-degree accumulations for each species (they have different lower developmental thresholds), the number of generations per year, the population density, and the date of the peak population were mapped. Overwintering survival for resident species and date of first immigration and number of immigrants for migrant species were also mapped.

### ***Analysis***

Climate warming from 1901 to about 1975 was fairly minor, in line with historical variation, but since 1975 the “hockey stick” curve shows a major temperature increase. The CO<sub>2</sub> increase started well before the observed temperature increase. The “CM2-SRES\_B1” scenario is based on an increase in CO<sub>2</sub> that stabilizes at 550ppm in 2100. As a result, temperature increase is most rapid from 2000 to 2050 with the rate of increase slowing after 2050. Thus, we expected little or no change in crop productivity and insect performance from 1901 to 2000, rapid change between 2000 and 2050 and reduced change from 2051 to 2100. These expectations were tested by mapping the average crop yields and pest performance for the four time periods 1901-1950, 1951-2000, 2001-2050, and 2051-2100, and creating difference and relative change maps. Difference maps were calculated by subtracting a map of  $j$  period from the map of period  $i$ :  $D_{ji} = M_j - M_i$ . Four difference maps were computed: change from Period 1 to Period 2, Period 2 to 3, Period 2 to 4 and Period 3 to 4. Relative change maps were computed for some variables from  $R_{ji} = D_{ji}/M_i$ .

### ***Results***

32,520 different simulations were run, each for 50 years. Each simulation produced four output files: two annual summary files and two daily files that totaled 65MB. The entire experiment produced 2.1TB of output. These files were filtered and reduced to a set of nine databases for the GIS. A GIS was created for each of the nine pests and the seven, eight, or nine variables were mapped for each species as appropriate. In all 775 maps were created from the simulations, including 20 climatological maps (precipitation, and summer and winter maximum and minimum temperatures for each time period). A selection of maps is presented in Figs. 1-8.

As expected, most maps changed little from Period 1 to 2 and substantially from Period 2 to 3. Change between Periods 3 and 4 were, in most cases, small and in a few cases the changes reversed the trend of the previous half century, but in no case were maps restored to their pre-2000 state. The best predictor of both insect abundance and crop loss is the annual accumulated day-degrees. Population growth started earlier, as a result of earlier break in diapause of the overwintering stage of resident species. Similarly, for migratory insects the earliest immigrant arrived earlier and the number of immigrants increased from Period 2 to 3. Peak populations, tended to be later for both immigrants and residents. Thus the exposure period of crops to pests increased and was partially responsible for increased crop loss. Specific observations for the nine pests follow.

### **Bean Leaf Beetle**

Mexican bean beetle is a resident pest on soybeans that is currently only a problem in southern Missouri and western Kentucky. In period 3 it is predicted to have increased its population by an order of magnitude, due to a doubling of the overwintering survival, an earlier onset of development, and later peak population. Crop loss is expected to increase over most of the range; only NW Nebraska and Ohio, will show little change. Kansas, Missouri, western Kentucky and southern Iowa and Illinois are expected to see damage levels increase to 50-80% without control.

### **Mexican Bean Beetle**

The model predicted only small change in Mexican bean beetle population between Periods 1 and 2 in line with experience. Over the next century, the number of generations is expected to increase from 2-3 to 4-5 over much of the range. This will result in substantial increases in population density over almost the entire range, except for NE Ohio and extreme NW Nebraska. The biggest increase in population will be in Kansas, Missouri, and southern Iowa and Illinois. Unlike most of the other insects in the study, the biggest increase in population and damage potential will be in Period 4, not Period 3. Overwinter survival is currently highest in southern Kansas, Missouri and Kentucky. By Period 3 peak overwinter survival will have moved north to central Illinois, southern Iowa and northeastern Kansas, which will increase the damage potential across the central part of the region.

### **Armyworm**

Armyworm invasions were predicted to occur earlier across the study area, with the largest change occurring at the western end, with Kansas, in particular experiencing immigration of this species 1-week earlier with a 10-15% increase in the number of immigrants in Period 3 over Period 2. Increased temperatures combined with earlier invasions and longer growing season permitted an extra generation over most of the region. The extra generation will permit much higher populations to develop. Without control measures, only Ohio would not see a dramatic increase in damage due to armyworm in the next half century, with near 100% crop loss in some areas in most years. Ohio would see a 50% increase in crop loss to armyworm. This increase in damage may be attributed to the increase in immigration rate combined with more rapid population growth resulting from the anticipated 20% increase in annual day-degree accumulations across most of the region. In the extreme northwest the increase approaches 40%. The increased yield loss predicted for Ohio is due to the large increase in growing season with only slight reduction in precipitation and modest increase in immigration. Without damage by armyworm, the model predicts a 50% increase in corn yield for Ohio resulting from the higher temperatures with only slight reduction in rainfall.

### **Black Cutworm**

Black cutworm and armyworm have very similar life histories, but differ in their developmental thresholds and fecundities. Black cutworm has a higher developmental threshold and lower reproductive rate; both these factors contribute to lower black cutworm population growth rate and slightly longer generation time, lower total population, and damage potential. As for armyworm, the biggest change in population density of black cutworm will occur from Period 2 to Period 3, with very small increases from Period 1 to Period 2 (in accordance with experience) and from 3 to 4. However, black cutworm populations were lower (with

proportionately lower relative change also) across the region than armyworm and increased the number of generations by less than 0.5 on average between Periods 2 and 3, the time frame with the largest change. As with armyworm, crops in the western end of our region are most at risk. The reduced annual precipitation puts both crops in stress, decreasing their growth rate and increasing susceptibility to insect damage.

### **Corn Earworm**

Corn earworm is both a resident and immigrant over most of our study area. It is an important pest of corn and an occasional pest of soybeans. Damage to soybeans will increase across the southern part of the region, especially in Period 3. There was little (< 5%) increase in soybean damage in the first and last periods; damage in Period 3 is expected to increase 35% to 65% across Missouri and Kansas. Little change is expected in the northern tier, including Ohio. For corn, the biggest impact is predicted to be in the northern tier from Indiana to Nebraska. A small increase in immigration rate is predicted over most of the region, but a large increase is predicted for Kansas and Nebraska. The major determinant of increased crop loss is due to the up to three-fold increase in overwintering survival in the southern tier and increased migration northward, occurring up to 2 weeks earlier in the west and one week earlier in the east. Population density was predicted to double over most of the range in Period 3 and to peak about 2 weeks later than in Periods 1 and 2.

### **European Corn Borer**

European corn borer is a resident species that attacks both corn and soybeans. Currently it is a minor pest on both crops (but an important pest on sweet corn). Damage to corn, but especially soybeans is predicted to increase in Period 3. Populations are predicted to more than double over most of the range, resulting from an increase in the number of generations from one or two in the north and three in the south central part, to two or three in the north and three or four in the south. The biggest increase is expected in Period 3, but a further smaller increase is expected for Period 4. Currently, NE Ohio usually has only one generation with two in western and southern Ohio. All of Ohio is expected to have two generations with occasional thirds. Thus, Ohio can expect to see damage to both field corn and soybeans in the second half of this century.

### **Stalk Borer**

Stalk borer is the only obligate univoltine species in the study. Currently it is a periodic serious pest throughout the southern part of the region. It is occasionally a problem in the northern tier. The model predicts little change from Period 1 to 2 and a large increase in population and damage potential in Period 3 with a smaller increase in Period 4. The northern tier of states is expected to see a doubling in population in Period 3 and corresponding increase in damage potential. Southeastern Kansas, Southern Missouri, and Kentucky will see little or no change in stalk borer population and damage potential. The largest increase in population is predicted for southern Iowa, northern Missouri and northeastern Kansas with damage potential increasing 60-70%. This probably results from a northward movement of the area of maximal winter survival: the overall survival across the region is not expected to change very much. The increase in population and damage potential is due to the earlier onset of the growing season.

### **Velvetbean Caterpillar**

Velvetbean caterpillar is a migrant into our region. It is predicted to immigrate up to two weeks earlier in Period 3 than either Periods 1 or 2. This will provide sufficient time for at least

one extra generation per year over the entire range resulting in a doubling of the peak population density which will occur about two weeks later than at present. Damage potential is currently modest throughout the region except for southern Missouri and southeastern Kansas. However, the addition of a generation could result in a doubling of the damage potential across the region, with the largest increase in eastern Kansas, northwestern Missouri and southwestern Iowa. Ohio is unlikely to see any change.

### **Potato Leafhopper**

The moth migrants are all active fliers, able to migrate northwards in spring without wind assistance, whereas potato leafhopper is a weak flier that can only fly any distance by taking advantage of the wind. Potato leafhopper behavior is adapted to take advantage of the regular and repeatable wind patterns that form in the central part of the country. They migrate northwards up the “Mississippi Flyway” in spring and return to overwintering areas south of the 36<sup>th</sup> parallel in late summer on the northerly airflows following the passage of a frontal system. Potato leafhopper is highly polyphagous and is very common in the northern tier of states throughout the summer. At present it is an occasional pest on soybeans, causing “hopper burn” that reduces translocation and photosynthetic area. However, owing to its fairly rapid generation time, a lengthening of the growing season could result in an increase in the number of generations and therefore a change in its pest status. The model predicts the arrival of immigrants two weeks earlier in Period 3 than in Period 2, resulting in at least one extra generation across the range. As a result, the model predicts a big increase in population and damage potential across the northern five states. Its poor tolerance of high temperatures, will result in little change in pest status in Kentucky and even a slight reduction in southern Kansas and Missouri. Ohio is expected to see an increase in population and damage potential in Period 3 followed by a small decrease in period 4.

### **Discussion**

The increase in day-degree accumulation is the best predictor of increased potential pest pressure. Potential pest pressure is strongly influenced by the number of generations, which is a function of the onset of population growth, which in turn depends on when the developmental threshold is exceeded. The most obvious generalization to be drawn from these results is that insects with lower developmental thresholds become active earlier and this is true for both residents and migrants. However, the higher the threshold, the larger the *percentage increase* in accumulated degree-days because the *numerical increase* in degree-days is roughly the same for low and high threshold species. This appears to be true for both residents and for migrants, although the timing of the first immigration is probably more significant than developmental threshold. The stalk bore, which is univoltine, probably does not have sufficient time to go through a second generation anywhere in our region – assuming a mutation such as is seen occasionally in gypsy moth. Its increase in potential pest pressure is due entirely to the increased probability of winter survival. For the other resident species, including corn earworm which is also a migrant, the increase in overwinter survival and earlier onset of development will result in larger summer populations and an extra generation over much of the range. Potato leafhopper is an excellent example of an insect that is currently an occasional minor pest (easily controlled when other insects are controlled) that could become a more important pest as temperatures increase and seasons lengthen.

### **Objective III – Strategies for Sustainability**

With the high likelihood that climate warming is resulting in earlier and longer growing seasons for both crops and pests, the best strategy for pest control is to disrupt the life cycle as much as possible. For migrant species overwintering outside our region, management of the overwintering population is likely to be the best option. This is beyond the scope of this project. Control of the immigrants following invasion is the only other option, which will continue to emphasize pesticides and insect resistant varieties. Later planting dates (i.e. not taking advantage of the longer growing season) could be a constructive approach to desynchronize the crop and pest. For resident species, managing the overwintering population is a viable option. The longer growing season, opens more options for manipulating the timing of crops in order to reduce the susceptibility of the crop to pest attack. These options may reduce the impact of one species, but favor another. Thus, the choice of strategy is likely to be site-dependent. One strategy we believe would be effective across our study area is increasing the diversity of crops and the length of rotations. One of the best adaptive strategies would be to increase the rotation or diversify the cropping pattern. Planting wheat in the corn-soybean rotation has the advantage of a) lessening the effect of the corn borer b) decreasing the need for nitrogen fertilizer and c). decrease the runoff rate especially if coupled with no-till. wheat in corn soybean rotation, plant shorter season varieties of corn and soybeans The corn-soybean rotation has become the sole farming option for a large fraction of farmers across the Midwest since the 1970's. The new pest pressures resulting from climate warming will make longer and more complex rotations adaptive strategies. To encourage a move away from the dominant corn-soybeans-corn agriculture of the past four decades we propose that socio-economic pressures to decrease tenancy rates are likely to have a high probability of success.

Corn for grain, according to the 2007 Census of Agriculture, has a high rate of tenancy with the US farm total of 347,760 full owners, 115,664 part-owners, and 191,127 as tenants with the highest rate of tenancy existing in the larger scale of farm management (farms >500 acres). It is expected that long season corn and soybeans and lack of conservation measures exist in their highest percentages among tenants. For these farms, introducing wheat as a cover crop is less likely because fall planting requires that the corn and soybeans have been harvested and for long season varieties this window in September and October for planting is somewhat difficult depending on the weather. Short season varieties make winter cover crops much more feasible and are being promoted by the no-till groups in Ohio.

### **Discussion**

This project addressed the question “How will climate change alter pest-crop relationships and how will those changes impact agriculture?” Our objective is to identify and quantify the impact of changes to the agro-ecosystem that could adversely affect agriculture, the environment, and society. Knowledge of the expected changes in agricultural yield and pest pressure under climate change are minimal and the likely environmental and societal problems resulting from these changes are completely unknown. In this project we were directly concerned with the sustainability of corn and soybean agriculture over half a million square kilometers of the Midwest. Unanticipated changes to pest management needs could severely impact agricultural sustainability by necessitating new and possibly expensive pest management tactics. Early warning of pest management needs will permit research and extension to be ready with programs that do not require chemical control or permit prudent use of chemicals to the

advantage of farmers, consumers, and the environment.

American agriculture uses billions of dollars of pesticides per year and there is increasing pressure to cut the amount and toxicity of pesticides. Part of the purpose of pesticides is to insure that the crop is not lost to pests and like any insurance premium, the price is paid to avoid unanticipated and extreme costs later. The appearance of new pests, the increase in severity, or change in distribution of existing pests will require the payment of new insurance premiums in the form of pesticides until alternative pest management programs can be instituted. The value of anticipating those changes in pest status is measured in the billions of dollars in cash terms and is incalculable in environmental, societal, and human health terms.

This project has provided insights into the possible changes in pest status of nine insect pest commonly found across the corn belt. The emergence of new pests always leads to an increased use of chemical pesticides until alternative pest management programs using reduced or no chemicals can be put in place. The ability to anticipate new or changed pest pressures will enable relevant agencies help farmers adapt quickly to the changing conditions. The model output supports the conclusion that rapid changes in pest pressure are likely to occur over the next half century if temperatures increase as predicted by the GFDL global circulation model.

Although this project emphasizes the agricultural consequences of climate change, we recognize the interactive nature of agriculture and environment by considering the likely societal costs to changes in agricultural sustainability and increased pesticide use in response to increasing pest pressure..

The project was founded on the concept that the key mechanisms to understanding the impact of climate change on plant-pest interactions are the effects of differential thermal requirements of pest insects and crop plants on their phenology and synchrony. The changes in regional climate are clearly manifested, directly and indirectly, in changing position of isoclines of temperature and rainfall, resulting in consequential changes in the isoclines of crop and pest phenology, amount of crop damage, and other indicators of the crop-pest interaction. For all insects modeled such shifts were especially pronounced in the first half of the 21<sup>st</sup> century, although the geographic details differed markedly between species.

Our original hypothesis was that site-specific pest status would change, because we anticipated both increases and decreases in abundance locally. In most cases we found that population increases occurred across our range, but in two cases (stalk borer and potato leafhopper) we found little of slightly negative change in abundance in the southern part of the range with the maximal isoclines moving northward as the “ideal” climate moved north.

These results confirm that global warming in the northern hemisphere will have the effect of extending insect species ranges northward and will be most evident in *r*-selected migrant and/or multivoltine species that can exploit rising temperatures by increasing the number of life cycles per year (Fielding et al 1999). The non-migratory univoltine stalk borer showed a smaller geographical displacement, possibly because of the temperature-mitigating responses of diapause and the relative stability of the length of developmental period. Species with low adaptability and/or dispersal capability will be caught by the dilemma of climate-forced range change and low likelihood of finding distant habitats to colonize, ultimately leading to increased extinction rates. Needless to say, the situation is reversed for highly mobile species like potato leafhopper that are adapted to explore large tracts for suitable habitat.

As global warming progresses, we may also expect to see some new pests emerging as changing conditions create new niches. Although we cannot predict which species are likely to emerge as new pests, the general insights obtained will enable us to specify the life-history characteristics of such insects. By anticipating the preadaptations necessary to favor emergence as a new pest we should be able to plan for new pests and prepare ecologically sound management options..

Although species have responded to climatic changes throughout their evolutionary history, of primary concern is the rapid rate of change demonstrated by Mann et al (1998,1999). During previous climate changes, species showed differential movements (Root et al 2003), rather than shifting together as suggested by many authors, including Darwin (1859). Analyses of the likely effects of climate change have all attempted to assess impact at a regional, and in a few cases global, scale. These estimates have been derived from two approaches: point estimates scaled up to the desired region and spatially-explicit computations using mapping to display the results. The former has the advantage that it is comparatively quick and less demanding of data, while the latter approach allows for the sometimes extreme spatial variation in crop performance, and other biotic variables (Hobbs 1994). Our approach is slightly different in that it replicates the point estimate approach at the county scale over a region comprising over 800 counties. It was computationally very intensive, generating an enormous quantity of output for data reduction and analysis. As computing time is cheap, this approach is viable and the results show it to be a productive approach when combined with a geographic information system for visualization.

## References

### References

- Allen, JC. 1976. A modified sine wave method for calculating degree days. *Environ. Entomol.* 5:388-396.
- Carter, TR. & Saarikko, RA. 1996 Estimating regional crop potential in Finland under a changing climate. *Agric. For. Meteorol.* 79:301-313.
- Chmielewski, FM. 1992. Impact of climate changes on crop yields of winter rye in Halle southeastern Germany 1901 to 1980. *Climate Res.* 2:23-33.
- ESRI (2008)
- Fielding, CA, Whittaker, JB, Butterfield, JEL & Coulson, JC. 1999. Predicting responses to climate change: the effect of altitude and latitude on the phenology of the spittlebug *Neophilaenus lineatus*. *Funct. Ecol.* 13:65-73.
- Harrington, R, Woiwod, I & Sparks, TH. 1999. Climate change and trophic interactions. *Trends Ecol. Evol.* 14:146-150.
- Hobbs, RJ. 1995. Dynamics of vegetation mosaics: Can we predict responses to global change? *Ecoscience* 1:346-356.
- Hodgkinson, ID, Bird, J, Miles, JE, Bale, JS & Lennon, JJ. 1999. Climatic signals in the life histories of insects: the distribution of abundance of heather psyllids (*Strophingia* spp.) in the UK. *Funct. Ecol.* 13:83-95.
- Jonzen, N & 16 others. 2006. Rapid advance of spring arrival dates in long-distance migratory



- birds. *Science* 312:1959-1961.
- Kerr, RA. 2006. Politicians attack, but the evidence for global warming doesn't wilt. *Science* 313:421.
- Long, SP, Ainsworth, EA, Leakey, ADB, Nösberger, J & Ort, DR. 2006. Food for thought: lower-than-expected crop yield increase with rising CO<sub>2</sub> concentrations. *Science* 312:1918-1921.
- Mann, ME, Bradley, RS & Hughes, MK. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* 392:779-787
- Mann, ME, Bradley, RS & Hughes, MK. 1999. Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophys. Res. Lett.* 26:759-762.
- Myneni, RB, Keeling, CD, Tucker, CJ, Asrar, G & Nemani, RR. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* 386:698-702.
- Nicholls, N. 1997. Increased Australian wheat yield due to recent climate trends. *Nature* 387:484-485.
- Nonhebel, S. 1996. Effects of temperature rise and increase in CO-2 concentration on simulated wheat yields in Europe. *Climatic Change* 34:73-90.
- Penuelas, J & Filella, I. 2001. Responses to a warming world. *Science* 294:793-795.
- Pounds, JA & 13 others. 2006. Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature* 439:161-167.
- Riha, SJ, Wilks, DS & Simoens, P. 1996. Impact of temperature and precipitation variability on crop model predictions. *Climatic Change* 32:293-311.
- Root, TL, Price, JT, Hall, KR, Schneider, SH, Rosenzweig, C & Pounds, JA. 2003. Fingerprints of global warming on wild animals and plants. *Nature* 421:57-60.
- Rosenzweig, C & Parry, ML. 1994. Potential impact of climate changes on world food supply. *Nature* 367:133-138.
- Sanz, JJ, Potti, J, Moreno, J, Merino, S & Frias, O. 2003. Climate change and fitness components of a migratory bird breeding in the Mediterranean region. *Glob. Change Biol.* 9:461-472.
- Scherm, H. 2004. Climate change: can we predict the impacts on plant pathology and pest management? *Can. J. Plant Pathol.* 26: 267-273.
- Schiermeier, Q. 2006. The costs of global warming. *Nature* 439:374-375.
- Sehgal, M, Das, S, Chander, S, Gupta, NC & Kalra, N. 2006. Climate studies and insect pests - Implications for the Indian context. *JI Outlook Agric.* 35:33-40.
- Sharpley, AN & Williams, JR, Eds. 1990. EPIC--Erosion/Productivity Impact Calculator: 1. Model Documentation. U.S. Dept. Agric. Tech. Bull. No. 1768.
- Stinner, BR, Taylor, RAJ, Hammond, RB, Purrington, FF, McCartney, DA, Rodenhouse, N & Barrett, GW. (1989) Potential effects of climate change on plant-pest interactions. Pp. 8:1-35 in JB Smith & DA Tirpak (Eds) *The Potential Effects of Global Climate Change on The United States. Appendix C - Agriculture.* (USEPA Office of Policy, Planning and

- Evaluation, PM-221). U.S. Environmental Protection Agency, Washington, D.C.
- Stinner, RE, Rabb, RL & Bradley, JR. 1974. Population dynamics of *Heliothis zea* and *H. virescens* in North Carolina: a simulation model. *Environ. Entomol.* 3:163-168.
- Stouffer, RJ, Broccoli, AJ, Delworth, TL, Dixon, KW, Gudgel, R, Held, I, Hemler, R, Knutson, T, Lee, H-C, Schwartzkopf, MD, Soden, B, Spelman, MJ, Winton, M & Zeng, F. 2006. GFDL's CM2 Global coupled climate models. Part IV: Idealized climate response. *Journal of Climate* 19:723-740.
- Virtanen, T, Neuvonen, S, Nikula, A, Varama, M & Niemela, P. 1996. Climate change and the risks of *Neodiprion sertifer* outbreaks on Scots Pine. *Silva Fennica* 30:169-177.
- Visser, ME & 13 others. 2003. Variable responses to large-scale climate change in European *Parus* populations. *Proc. R. Soc. Lond. Ser. B* 270:367-372
- Volney, WJA & Cerezke, HF. 1992. The phenology of white spruce and the spruce budworm in northern Alberta. *Can. J. For. Res.* 22 :198-205.
- Volney, WJA & Fleming, RA. 2000. Climate change and impacts of boreal forest insects. *J. Agric. Ecosyst. Environ.* 82:283-294.
- Walther, GR & 8 others. 2002. Ecological response to climate change. *Nature* 416:389-395.
- Williams, DW & Liebhold, AM. 1995. Forest defoliators and climatic change: Potential changes in spatial distribution of outbreaks of western spruce budworm (Lepidoptera: Tortricidae) and gypsy moth (Lepidoptera: Lymantriidae). *Environ. Entomol.* 24:1-9.
- Woods, A, Coates, KD & Hamann, A. 2005. Is an unprecedented dothistroma needle blight epidemic related to climate change? *Bioscience* 55:761-769.

Model Variable	Stage	I	II	III	IV	V
<b>Bean Leaf Beetle (<i>Ceratoma trifurcata</i>)</b>						
Migration status (resident = 0, migrant = 1)		0				
Voltinism (univoltine = 1, multivoltine > 1)		2				
Stages (adult stage #; maximum = 8)		4				
Overwintering stage (1-8; migrant ignored)		4				
Starting population (#/ha; migrant ignored)		100				
		0				
Starting age distribution (days; migrant ignored)		20				
Sex ratio (proportion of females)		0.5				
Eggs per female/day		40				
Proportion surviving frost		0.2	0.3	0.6	0.98	
Dailysurvival rate (1.0 - daily mortality rate)		0.95	0.95	0.98	0.95	
Overwintering/Immigrating generation - Stage duration (max days)		0	0	0	125	
Degree days (C)		0	0	0	30	
Summer generation - Stage duration (max days)		21	30	30	30	
Degree days (C)		120	120	250	0	
Developmental threshold (C) - Upper		30	30	30	30	
Developmental threshold (C) - Lower		10	10	10	10	
Feeding rate (mg/day)		0	2	0	5	
Damaging generation(s) (corn)		0	0			
Impact % per insect per plant (corn)		0	0	0	0	
Damaging generation(s) (beans)		1	1			
Impact % per insect per plant (beans)		0	3	0	10	
Migrant - first & last flight months						
Migrant - Flight threshold (degrees C)						
Migrant - Immigration rate (#/ha/day/km daily windrun)						
<b>Mexican Bean Beetle (<i>Epilachna varivestis</i>)</b>						
Migration status (resident = 0, migrant = 1)		0				
Voltinism (univoltine = 1, multivoltine > 1)		4				
Stages (adult stage #; maximum = 8)		4				
Overwintering stage (1-8; migrant ignored)		4				
Starting population (#/ha; migrant ignored)		250				
		0				
Starting age distribution (days; migrant ignored)		10				
Sex ratio (proportion of females)		0.5				
Eggs per female/day		30				
Proportion surviving frost		0.5	0.5	0.7	0.99	
					9	
Dailysurvival rate (1.0 - daily mortality rate)		0.9	0.9	0.9	0.95	
Overwintering/Immigrating generation - Stage duration (max days)		0	0	0	170	
Degree days (C)		0	0	0	75	
Summer generation - Stage duration (max days)		0	0	0	20	
Degree days (C)		75	220	90	0	

Model Variable	Stage	I	II	III	IV	V
Developmental threshold (C) - Upper		30	30	30	30	
Developmental threshold (C) - Lower		11.5	11.5	11.5	11.5	
Feeding rate (mg/day)		0	5	0	2	
Damaging generation(s) (corn)		0	0	0	0	
Impact % per insect per plant (corn)		0	0	0	0	
Damaging generation(s) (beans)		1	1	1	1	
Impact % per insect per plant (beans)		0	15	0	5	
Migrant - first & last flight months						
Migrant - Flight threshold (degrees C)						
Migrant - Immigration rate (#/ha/day/km daily windrun)						
<b>Armyworm (<i>Pseudaletia unipuncta</i>)</b>						
Migration status (resident = 0, migrant = 1)		1				
Voltinism (univoltine = 1, multivoltine > 1)		4				
Stages (adult stage #; maximum = 8)		4				
Overwintering stage (1-8; migrant ignored)		0				
Starting population (#/ha; migrant ignored)		0				
Starting age distribution (days; migrant ignored)		0				
Sex ratio (proportion of females)		0.5				
Eggs per female/day		20				
Proportion surviving frost		0.5	0.5	0.5	0.5	
Dailysurvival rate (1.0 - daily mortality rate)		0.98	0.95	0.98	0.9	
Overwintering/Immigrating generation - Stage duration (max days)		0	0	0	10	
Degree days (C)		0	0	0	0	
Summer generation - Stage duration (max days)		15	10	10	15	
Degree days (C)		80	360	170	0	
Developmental threshold (C) - Upper		30	30	30	30	
Developmental threshold (C) - Lower		8	8	10	10	
Feeding rate (mg/day)		0	6	0	0	
Damaging generation(s) (corn)		1	1	1	1	
Impact % per insect per plant (corn)		0	25	0	0	
Damaging generation(s) (beans)		0	0	0	0	
Impact % per insect per plant (beans)						
Migrant - first & last flight months						
Migrant - Flight threshold (degrees C)						
Migrant - Immigration rate (#/ha/day/km daily windrun)		0				
		.01				
<b>Black Cutworm (<i>Agrotis ipsilon</i>)</b>						
Migration status (resident = 0, migrant = 1)		1				
Voltinism (univoltine = 1, multivoltine > 1)		4				
Stages (adult stage #; maximum = 8)		5				

Model Variable	Stage	I	II	III	IV	V
Overwintering stage (1-8; migrant ignored)		0				
Starting population (#/ha; migrant ignored)		0				
Starting age distribution (days; migrant ignored)		0				
Sex ratio (proportion of females)		0.5				
Eggs per female/day		10				
Proportion surviving frost		0.5	0.5	0.5	0.5	0.5
Dailysurvival rate (1.0 - daily mortality rate)		0.98	0.98	0.98	0.98	0.98
Overwintering/Immigrating generation - Stage duration (max days)		0	0	0	0	20
Degree days (C)		0	0	0	0	0
Summer generation - Stage duration (max days)		10	15	20	15	30
Degree days (C)		90	230	330	350	0
Developmental threshold (C) - Upper		35	35	35	35	35
Developmental threshold (C) - Lower		8	8	8	8	8
Feeding rate (mg/day)		0	6	10	0	0
Damaging generation(s) (corn)		0	1	0	0	
Impact % per insect per plant (corn)		0	0	120	0	0
Damaging generation(s) (beans)		0	0	0	0	
Impact % per insect per plant (beans)		0	0	0	0	0
Migrant - first & last flight months		3	6			
Migrant - Flight threshold (degrees C)		15				
Migrant - Immigration rate (#/ha/day/km daily windrun)		0.01				
<b>Corn Earworm (<i>Heliothis zea</i>)</b>						
Migration status (resident = 0, migrant = 1)		1				
Voltinism (univoltine = 1, multivoltine > 1)		3				
Stages (adult stage #; maximum = 8)		4				
Overwintering stage (1-8; migrant ignored)		3				
Starting population (#/ha; migrant ignored)		0				
Starting age distribution (days; migrant ignored)		0				
Sex ratio (proportion of females)		0.5				
Eggs per female/day		40				
Proportion surviving frost		0.2	0.2	0.9	0.2	
Dailysurvival rate (1.0 - daily mortality rate)		0.98	0.95	0.98	0.9	
Overwintering/Immigrating generation - Stage duration (max days)		0	0	150	21	
Degree days (C)		100	200	180	0	
Summer generation - Stage duration (max days)		5	21	14	21	
Degree days (C)		100	200	180	0	
Developmental threshold (C) - Upper		34	34	34	34	
Developmental threshold (C) - Lower		12.5	12.5	12.5	12.5	
Feeding rate (mg/day)		0	6	0	0	
Damaging generation(s) (corn)		0	1	1		
Impact % per insect per plant (corn)		0	7	0	0	
Damaging generation(s) (beans)		1	1	1		
Impact % per insect per plant (beans)		0	2	0	0	

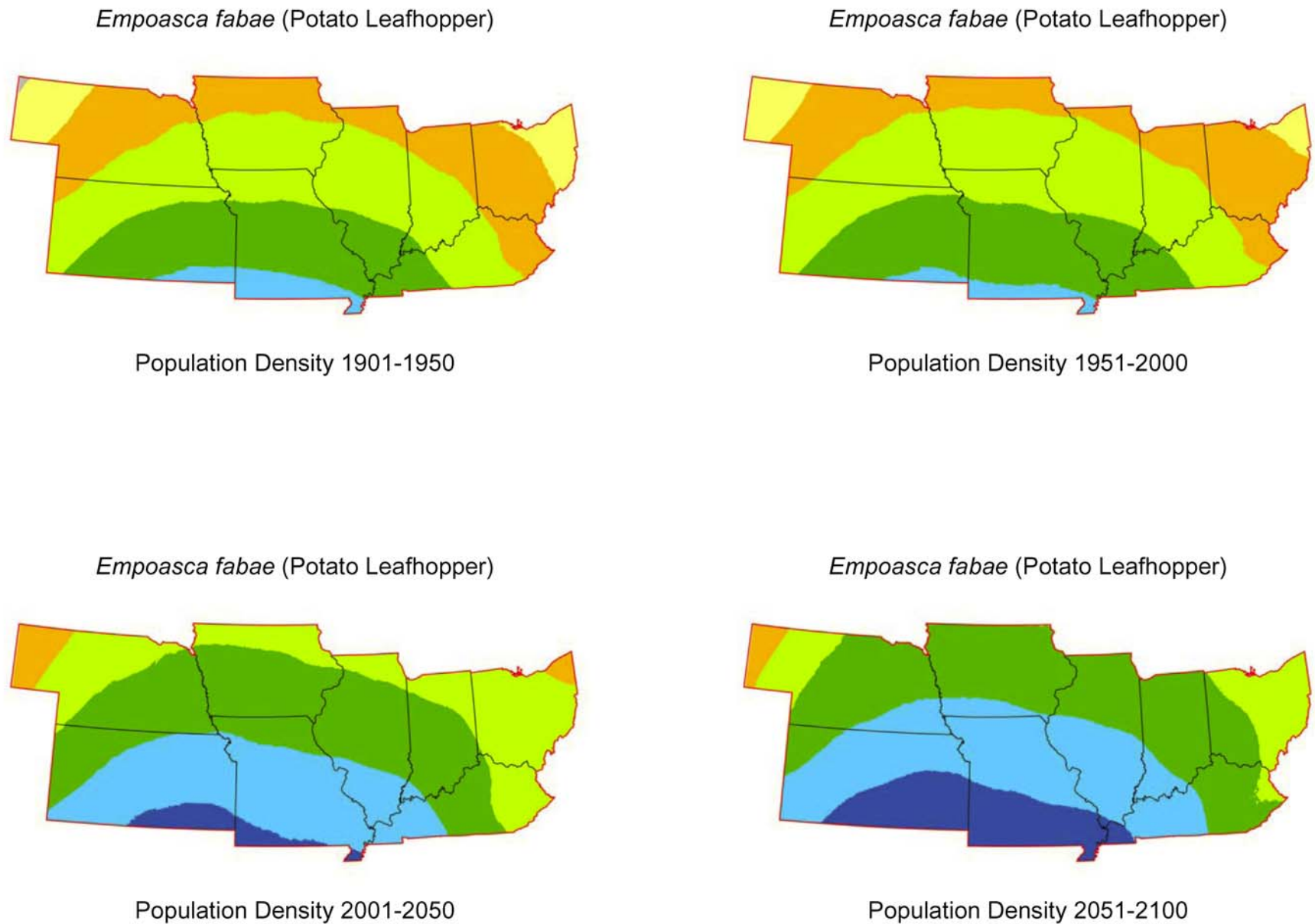
Model Variable	Stage	I	II	III	IV	V
Migrant - first & last flight months		3	6			
Migrant - Flight threshold (degrees C)		15				
Migrant - Immigration rate (#/ha/day/km daily windrun)		0.01				
<b>European Corn Borer (<i>Ostrinia nubilalis</i>)</b>						
Migration status (resident = 0, migrant = 1)		0				
Voltinism (univoltine = 1, multivoltine > 1)		4				
Stages (adult stage #; maximum = 8)		5				
Overwintering stage (1-8; migrant ignored)		3				
Starting population (#/ha; migrant ignored)		100				
		0				
Starting age distribution (days; migrant ignored)		20				
Sex ratio (proportion of females)		0.5				
Eggs per female/day		30				
Proportion surviving frost		0.5	0.5	0.98	0.5	0.5
Dailysurvival rate (1.0 - daily mortality rate)		0.95	0.95	0.95	0.95	0.9
Overwintering/Immigrating generation - Stage duration (max days)		0	0	0	0	10
Degree days (C)		0	0	185	165	0
Summer generation - Stage duration (max days)		0	0	0	0	10
Degree days (C)		165	165	165	165	0
Developmental threshold (C) - Upper		30	30	30	30	30
Developmental threshold (C) - Lower		10	10	10	10	10
Feeding rate (mg/day)		0	6	10	0	0
Damaging generation(s) (corn)		1	1	1	1	
Impact % per insect per plant (corn)		0	3	6	0	0
Damaging generation(s) (beans)		1	1	1	1	
Impact % per insect per plant (beans)		0	1	2	0	0
Migrant - first & last flight months						
Migrant - Flight threshold (degrees C)						
Migrant - Immigration rate (#/ha/day/km daily windrun)						
<b>Stalk Borer (<i>Papaipama nebris</i>)</b>						
Migration status (resident = 0, migrant = 1)		0				
Voltinism (univoltine = 1, multivoltine > 1)		1				
Stages (adult stage #; maximum = 8)		4				
Overwintering stage (1-8; migrant ignored)		1				
Starting population (#/ha; migrant ignored)		500				
		0				
Starting age distribution (days; migrant ignored)		60				
Sex ratio (proportion of females)		0.5				
Eggs per female/day		200				
Proportion surviving frost		0.98	0.5	0.3	0.1	
Dailysurvival rate (1.0 - daily mortality rate)		0.97	0.97	0.97	0.95	
Overwintering/Immigrating generation - Stage duration (max days)		0	75	30	10	
Degree days (C)		155	0	0	0	

Model Variable	Stage	I	II	III	IV	V
Summer generation - Stage duration (max days)						
Degree days (C)						
Developmental threshold (C) - Upper		30	30	30	30	
Developmental threshold (C) - Lower		9	9	9	9	
Feeding rate (mg/day)		0	20	0	0	
Damaging generation(s) (corn)		1				
Impact % per insect per plant (corn)		0	20	0	0	
Damaging generation(s) (beans)		1				
Impact % per insect per plant (beans)		0	20	0	0	
Migrant - first & last flight months						
Migrant - Flight threshold (degrees C)						
Migrant - Immigration rate (#/ha/day/km daily windrun)						
<b>Velvetbean Caterpillar (<i>Anticarsia gemmatilis</i>)</b>						
Migration status (resident = 0, migrant = 1)		1				
Voltinism (univoltine = 1, multivoltine > 1)		2				
Stages (adult stage #; maximum = 8)		5				
Overwintering stage (1-8; migrant ignored)		0				
Starting population (#/ha; migrant ignored)		0				
Starting age distribution (days; migrant ignored)		0				
Sex ratio (proportion of females)		0.5				
Eggs per female/day		30				
Proportion surviving frost		0	0.1	0.1	0.1	0.2
Dailysurvival rate (1.0 - daily mortality rate)		0.98	0.98	0.98	0.8	0.9
Overwintering/Immigrating generation - Stage duration (max days)		0	0	0	0	20
Degree days (C)		0	0	0	0	0
Summer generation - Stage duration (max days)		0	0	0	0	20
Degree days (C)		130	130	65	160	0
Developmental threshold (C) - Upper		35	35	35	35	35
Developmental threshold (C) - Lower		10.5	10.5	12.5	10.5	0
Feeding rate (mg/day)		0	25	65	0	0
Damaging generation(s) (corn)		0	0			
Impact % per insect per plant (corn)		0	0	0	0	0
Damaging generation(s) (beans)		1	1			
Impact % per insect per plant (beans)		0	15	25	0	0
Migrant - first & last flight months		6	7			
Migrant - Flight threshold (degrees C)		15				
Migrant - Immigration rate (#/ha/day/km daily windrun)		0.01				
<b>Potato Leafhopper (<i>Empoasca fabae</i>)</b>						
Migration status (resident = 0, migrant = 1)		1				
Voltinism (univoltine = 1, multivoltine > 1)		3				
Stages (adult stage #; maximum = 8)		3				
Overwintering stage (1-8; migrant ignored)		0				

Model Variable	Stage	I	II	III	IV	V
Starting population (#/ha; migrant ignored)		0				
Starting age distribution (days; migrant ignored)		0				
Sex ratio (proportion of females)		0.5				
Eggs per female/day		20				
Proportion surviving frost		0.5	0.1	0.1		
Dailysurvival rate (1.0 - daily mortality rate)		0.9	0.95	0.98		
Overwintering/Immigrating generation - Stage duration (max days)		0	0	20		
Degree days (C)		0	0	0		
Summer generation - Stage duration (max days)		0	0	35		
Degree days (C)		135	280	0		
Developmental threshold (C) - Upper		30	30	30		
Developmental threshold (C) - Lower		8	8	10		
Feeding rate (mg/day)		0	1	2		
Damaging generation(s) (corn)		0	0	0		
Impact % per insect per plant (corn)		0	0	0		
Damaging generation(s) (beans)		1	1	1		
Impact % per insect per plant (beans)		0	5	8		
Migrant - first & last flight months		3	7			
Migrant - Flight threshold (degrees C)		10				
Migrant - Immigration rate (#/ha/day/km daily windrun)		0.01				

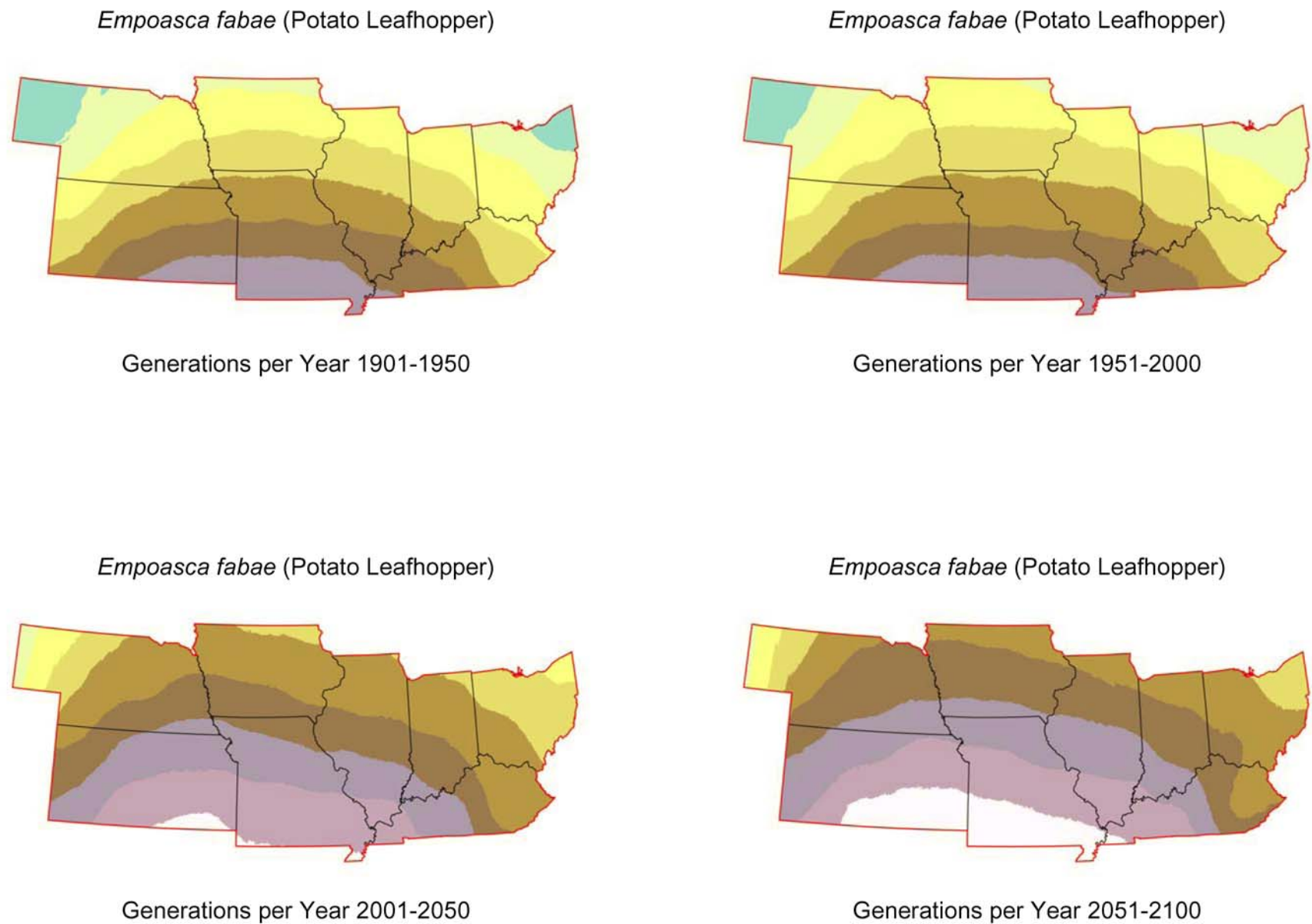


Figure 1: Little change in PLH population density in the 21<sup>st</sup> century; major increase in the first half of the 21<sup>st</sup> century



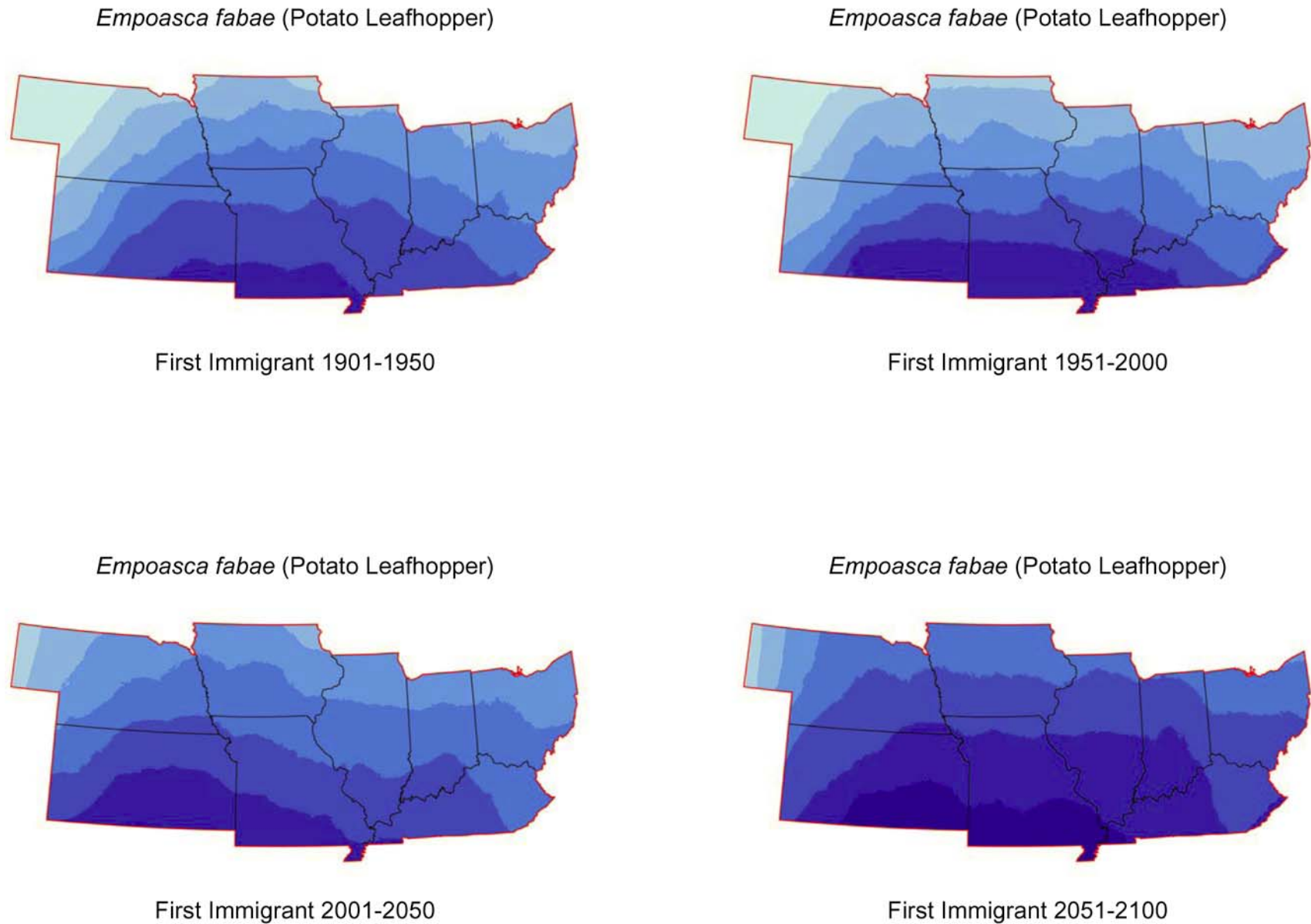
The isoclines for population density (blue is highest) moved little in the 21<sup>st</sup> century, but will move northward in the 21<sup>st</sup> century.

Figure 2: An increase in the number of generations of PLH is expected in the 21<sup>st</sup> century



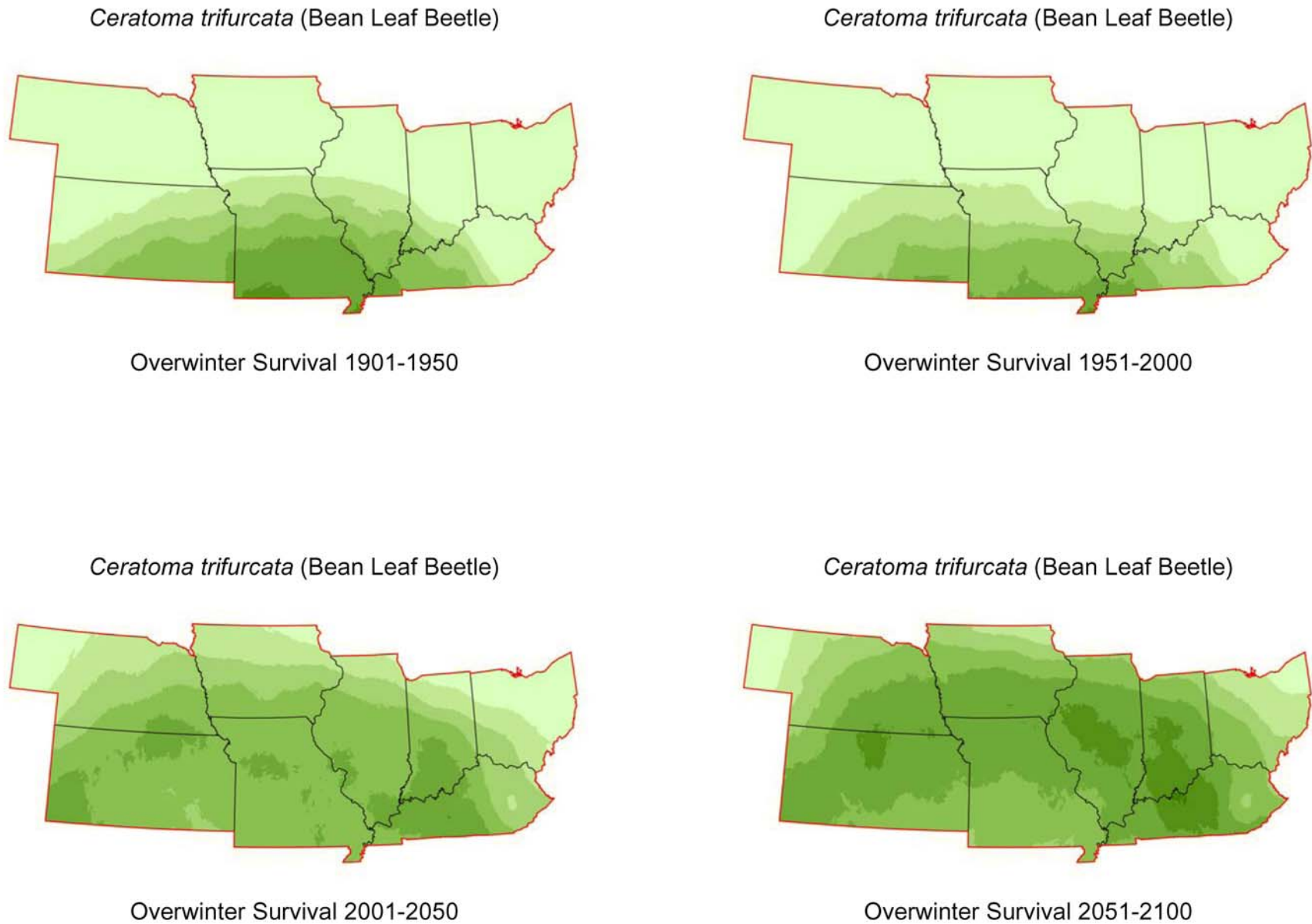
Increased population density will be enabled by the addition of a generation across the entire region

Figure 3: Potato leafhopper date of first arrival has been getting earlier for a century and this trend will continue in the 21<sup>st</sup> century



The darker the color, the earlier the date. The difference between 20<sup>th</sup> and 21<sup>st</sup> centuries for potato leafhopper is almost one month.

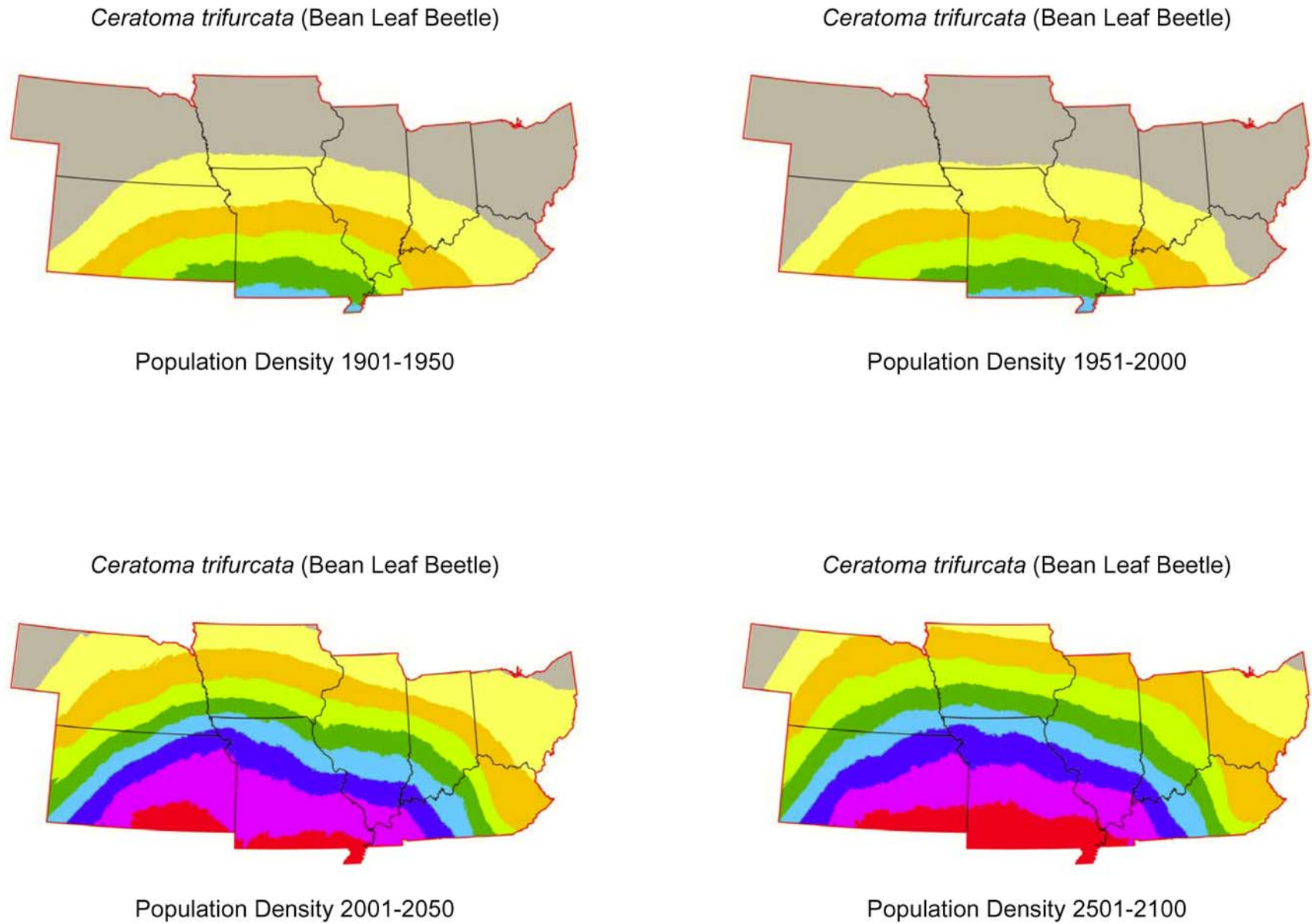
Figure 4: Overwintering survival of resident species is expected to increase in northern areas



Isoclines for overwintering survival (darker is higher survival) changed little in the 20<sup>th</sup> century, but will move northwards in the 21<sup>st</sup> century.

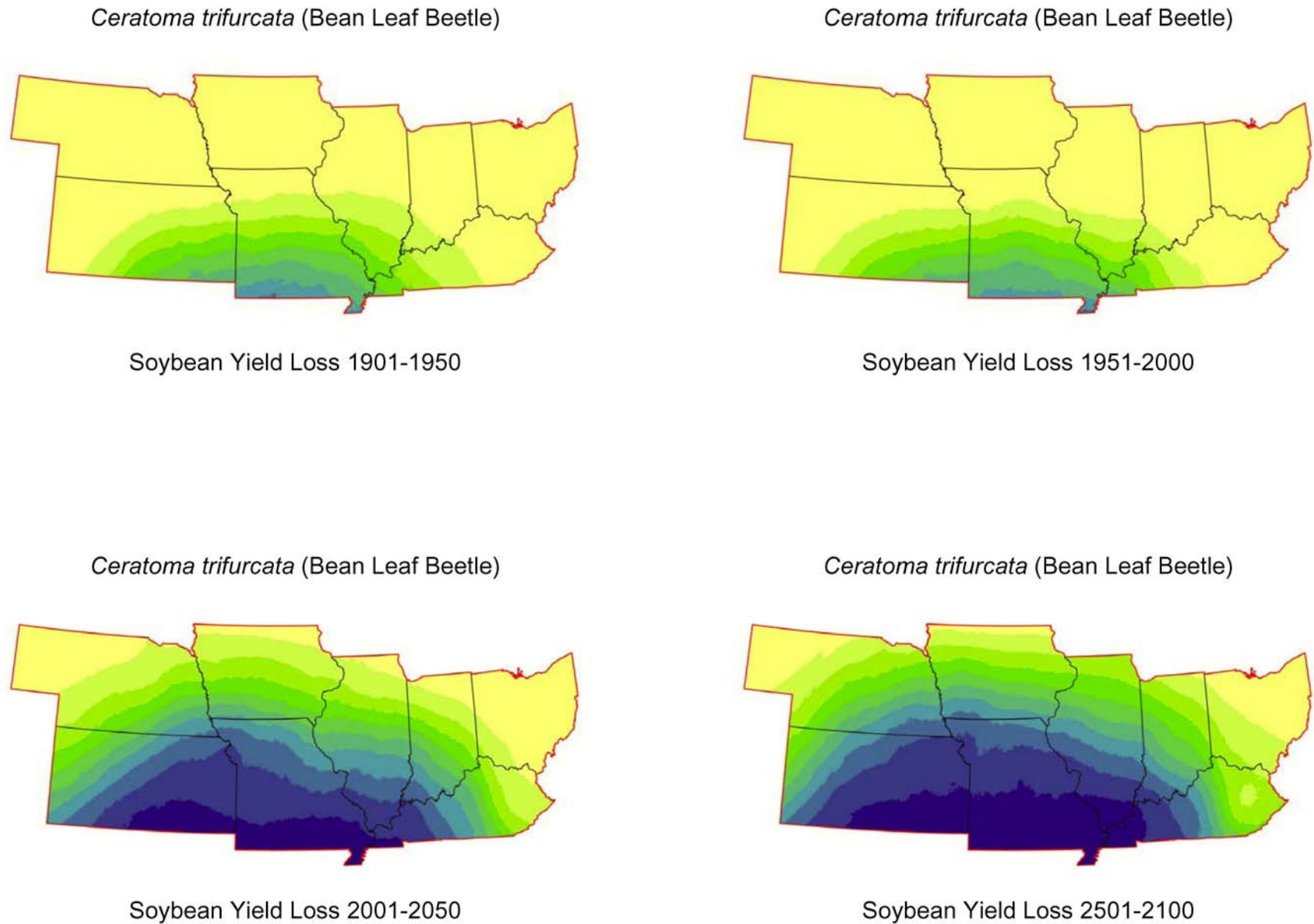


Figure 5: Earlier immigration will permit an extra generation in most areas



A large increase in bean leaf beetle populations is expected over the next 50 years (red is highest density).

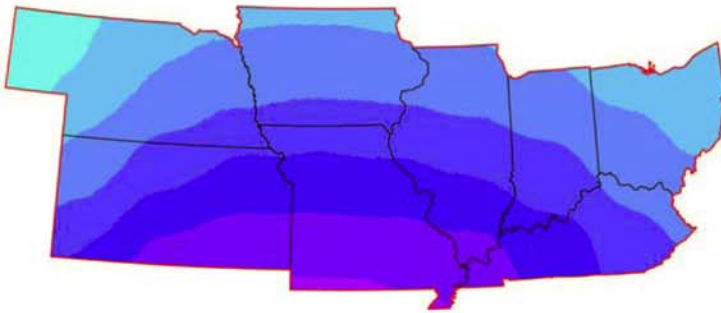
Figure 6: Increased overwintering survival combined with more rapid and earlier population growth could change pest status



Bean leaf beetle could become a serious pest in the 21<sup>st</sup> century in areas where it has typically been only an occasional problem

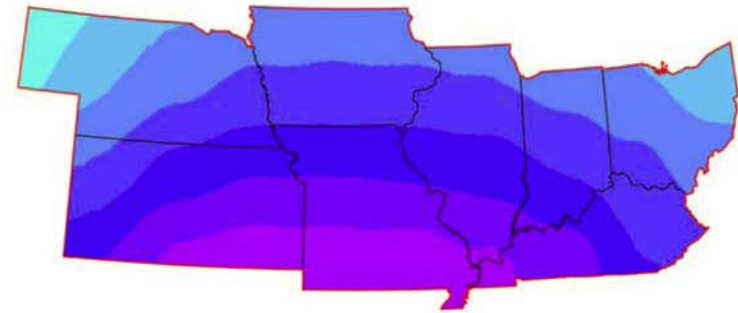
Figure 7: Annual day degree accumulation is the best predictor of population density and crop damage

*Heliothis zea* (Corn Earworm)



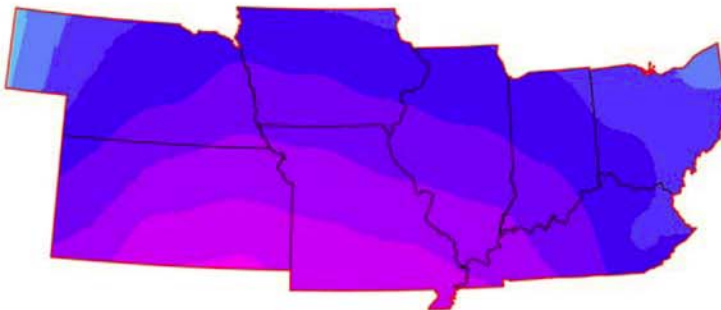
Day-Degrees (12.5°C Threshold) 1901-1950

*Heliothis zea* (Corn Earworm)



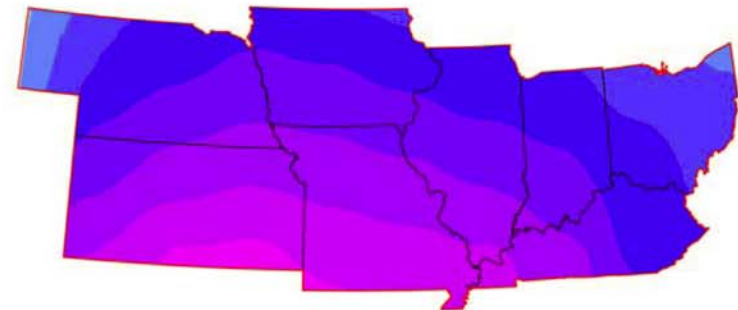
Day-Degrees (12.5°C Threshold) 1951-2000

*Heliothis zea* (Corn Earworm)



Day-Degrees (12.5°C Threshold) 2001-2050

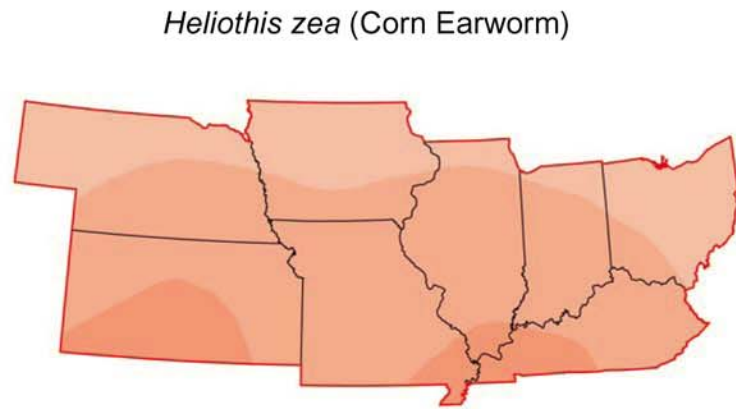
*Heliothis zea* (Corn Earworm)



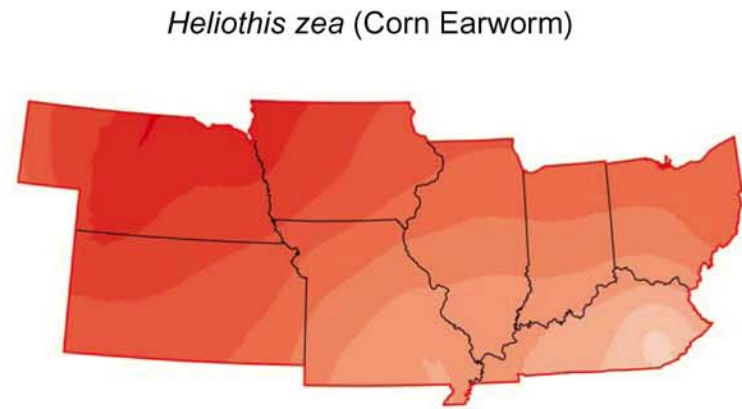
Day-Degrees (12.5°C Threshold) 2051-2100

The brighter color the greater the annual day-degree accumulation. The higher the developmental threshold the greater the risk.

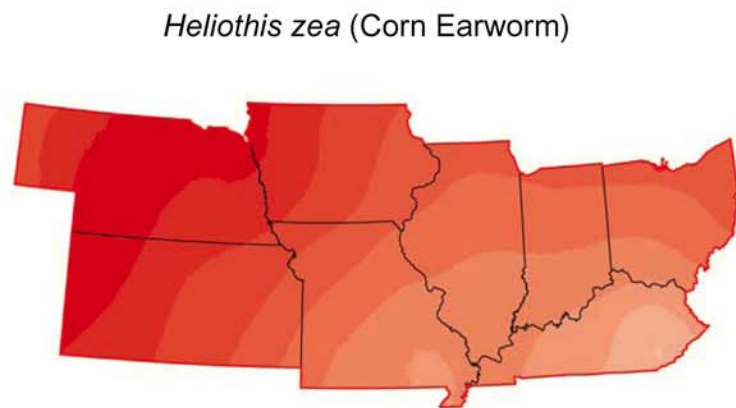
Figure 8: Difference maps show clearly the areas of greatest risk of changing pest status



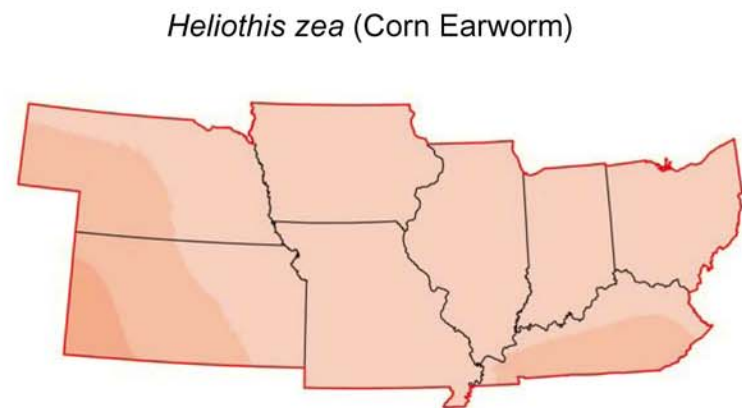
Day-Degrees Difference (Period II-I)



Day-Degrees Difference (Period III-II)



Day-Degrees Difference (Period IV-II)



Day-Degrees Difference (Period IV-III)

The darker the color, the greater the change in annual day-degree accumulation and the greater the risk of corn earworm pest damage.